**DOCUMENT NO. LBNL-45224**

# A REAPPRAISAL OF THE REPORTED DOSE EQUIVALENTS AT THE BOUNDARY OF THE UNIVERSITY OF CALIFORNIA RADIATION LABORATORY DURING THE EARLY DAYS OF BEVATRON OPERATION.


Richard J. Donahue

Alan R. Smith

Ralph H. Thomas

Gary H. Zeman

Ernest Orlando Lawrence Berkeley National Laboratory

Berkeley, California 94720



July 2001

To be submitted for publication in Radiation Protection Dosimetry

This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division of the U. S. Department of Energy, under Contract No. DE-AC03-76SF00098

**ABSTRACT**

The Bevatron of the Lawrence Berkeley National Laboratory operated with no permanent shielding-roof from 1954-1962. Neutron fluences measured at the laboratory perimeter reached a maximum in 1959, and were reported as a dose equivalent of 0.81 rem (8.1 mSv) [54% of the then operative radiation limit]. The addition of temporary local shielding and improved operational techniques subsequently led to a steady decline in dose equivalent at the laboratory perimeter. A permanent concrete shielding-roof was constructed in 1962.

In those early years of operation the reported dose equivalent, H, was derived from a measured total neutron fluence, $\Phi$, and an estimated spectrum-weighted fluence to dose equivalent conversion coefficient, <g>, where:

$$H = \langle g \rangle \, \Phi$$

The uncertainty in H in was almost entirely due to the uncertainty in <g>. While the measurements of $\Phi$ were quite accurate the estimates of <g> were quite crude and depended upon measurements of average neutron energy, on assumptions about the shape of the neutron energy spectrum, and primitive values of fluence to dose equivalent conversion coefficients for monoenergetic neutrons.

These early reported dose equivalents were known to be overestimated. This paper has reappraised the dose equivalents in the light of better information now available. Environmental neutron spectra have been calculated that more accurately correspond to the operational conditions of the Bevatron in the fifties and early sixties, than did those spectra available at that time. A new fluence to dose equivalent conversion function based on the latest data and for isotropic irradiation geometry was developed. From these two parameters better estimates of the coefficient <g> were determined and compared with the earlier values.

From this reappraisal it is shown that the early reported dose equivalents were conservative by a factor of at least five.

*"The absence of romance in our history will, we fear, detract somewhat from its interest; but we shall be content if it is judged useful by those inquirers who desire an exact knowledge of the past - - - -"*

*Thucydides*

*History of the Peloponnesian War*

**INTRODUCTION**

Interest has recently been revived in the magnitude of the neutron fluences, and their corresponding dose equivalents, produced at the boundary of the University of California Radiation Laboratory due to Bevatron operation, during the late fifties and early sixties (see footnote 1). From the first operation of the Bevatron measurements of neutron fluence were made at locations around the perimeter of the Lawrence Berkeley National Laboratory (LBNL). Since the late 1950's measurements made at several locations, and particularly at the site of what is now called the Olympus Gate Environmental Monitoring Station (EMS), have been routinely reported and published (see footnote 2).

Following the initial operation of the Bevatron neutron fluences measured at the laboratory boundary steadily increased with the increasing proton beam intensity. The annual neutron fluence reached a maximum in 1959 and then declined because of both improved efficiency of accelerator operation and the addition of temporary shielding[1,2]. A new permanent concrete shield was installed, including a concrete roof above the accelerator, in 1962[3-5].

By convention, radiological protection advisory organisations, such as the ICRP and NCRP express radiation intensities and dose limits in dose equivalent quantities (see footnotes 3 & 4). This convention was adopted by regulatory agencies of the United States, in particular the United States Atomic Energy Commission (USAEC) and its successors which regulated the operations of the Berkeley Laboratory. The 1958 regulations of the USAEC were greatly influenced by the recommendations contained in NBS Handbook 63[6,7].

At Berkeley neutron measurements were made with the purpose of determining the shape of the neutron differential energy-spectrum, ($d\phi/dE$), and the total neutron fluence, $\Phi$. The dose equivalent, H, corresponding to the total neutron fluence, $\Phi$, was obtained by the application of a spectrum-weighted fluence-to-dose-equivalent conversion-coefficient $<g>$. The values of both H and $<g>$ depend upon the irradiation geometry, G:

$$H_G = < g_G > \Phi \tag{1}$$

This conversion is discussed in detail later in this paper in the section entitled "Fluence to Effective Dose Conversion Coefficients".

Figure 1 shows the annual dose equivalents reported at the site boundary of Berkeley Laboratory during the early years of Bevatron operation. Between 1958 and 1961 the reported dose equivalents were a significant fraction of, but did not exceed, the recommended public annual dose equivalent limit[6,7] that was 15 mSv per annum (10% of the then current worker dose limit of 150 mSv per annum). In the decades since those early years the recommended public dose equivalent limit has been sequentially reduced, first to 5 mSv per annum and most recently to 1 mSv per annum. The fact that the past reported dose equivalents at the site boundary exceeded the now current public limit has prompted renewed interest in these earlier data and in the accuracy of the assumptions used to generate them. As a matter of policy the Berkeley Laboratory used the measurements of neutron fluence and an estimated conversion coefficient to compute dose equivalents. Best estimates of maximum dose equivalents supported by the data were then published and reported. It was fully understood at that time that the estimated conversion coefficient was conservative (high) and therefore that these reported dose equivalents were overestimates, but the information needed to determine the magnitude of this overestimation was not then available. Forty years later the means of obtaining a more precise interpretation of these early fluence measurements is now available and can be applied to a better understanding of accelerator-produced radiation at the laboratory boundary.

**THE BEVATRON**

The Bevatron was one of the first-generation weak-focussing proton synchrotrons to be constructed during the first decade following the end of the Second World War. It was designed to accelerate protons to a kinetic energy of 6.2 GeV with an initial beam intensity of $10^9$ protons per pulse, at a repetition rate of 10 pulses per minute. At this design intensity no significant radiation problems were expected at large distances from the synchrotron. Within a few months of its first operation in 1954 the design intensity was reached and within a year an intensity of $\sim 10^{10}$ protons per pulse was achieved. Improvements in operating efficiency increased the beam intensity and, as figure 1 shows, the number of protons accelerated per annum during the decade 1954-1964, increased by a factor of roughly 6000. Consequently there was an increasing potential for exposure to high-energy neutrons and photons similar in character to, but at greater intensities than, those resulting from the interaction of the cosmic radiation with the Earth's atmosphere. Shielding was placed around accelerator components as the radiation intensity increased and in 1962 extensive modifications were made which included the addition of shielding above the accelerator[(3-5)].

The Bevatron was a large, almost circular, accelerator with a circumference of about 126m. From early after its first operation it was contained within a cylindrical concrete shield-wall, about 2 m thick but with no permanent overhead shielding other than that provided by the magnet yoke and pole tips, amounting to about 1m steel. In those early years the close-in radiation field was largely determined by the leakage of intermediate-energy neutrons through the magnet yoke. Bevatron targets were placed in the vacuum chamber and proton losses could occur over large regions around the ring**.** Additional overhead concrete shielding was often placed over sources of radiation from the tangent tanks (straight sections), which had no magnets [(8)].

**ACCELERATOR RADIATION MEASUREMENTS.**

The philosophical basis for radiation monitoring at the Berkeley Laboratory was the systematic identification of the components and characteristics of high-energy radiation fields. This required the measurement of integrated particle fluence and energy spectra. Such a procedure had (and still has) the advantage that the physical data possess a permanence not typical of the ICRP and ICRU dose equivalent quantities (see footnote 5). It is, in principle, a relatively simple matter to determine the values of dose equivalents required by regulatory agencies with the use of appropriate fluence-to-dose-equivalent conversion coefficients (now referred to in what follows as "conversion coefficients") and this was the practice at the Berkeley Laboratory (see equation 1).

The neutron energy spectrum-averaged dose equivalent conversion coefficient, $\langle g_G \rangle$, of equation 1 is defined by:

$$< g_G >= \frac{\int_{E_{min}}^{E_{max}} g_G(E)\left(\frac{d\phi}{dE}\right)dE}{\int_{E_{min}}^{E_{max}} \left(\frac{d\phi}{dE}\right)dE} \qquad (2)$$

where:

$E_{min}$ and $E_{max}$ are the minimum and maximum energies of the neutron spectrum

$g(E)$ is the fluence-to-dose-equivalent conversion coefficient function for monoenergetic neutrons

$d\phi/dE$ is the neutron differential energy-spectrum

$G$ specifies the irradiation geometry

It follows from equations (1) and (2) that, provided both the neutron differential energy-spectrum and conversion function are known over the energy range from $E_{min}$ to $E_{max}$, the magnitude of the appropriate dose equivalent quantity may be determined.

The techniques of radiation measurement used at the Berkeley Laboratory have been fully described in the scientific literature. An excellent brief summary of the early techniques is given in NBS Handbook 72(9). Further information is given in, for example, Moyer(10,11), Paterson and Thomas(12) and IAEA Technical Report 283(13).

Many, probably most, of the routine neutron radiation surveys made around the Bevatron in the early 60's, including those at the site perimeter, were made using the detectors developed by Smith(14). Various thermal neutron activation foils were placed inside 6" diameter cylindrical polyethylene or paraffin moderators, encased in cadmium (Smith-Stephens detectors). These detectors were calibrated using $^{239}$PuBe neutron sources having an average neutron energy of about 4.2 MeV. This technique and much of the supporting dosimetry of that period has been described in reference(12).

No calculations of the energy response of indium activation foils placed in cylindrical moderators have been published but some experimental determinations have been reported for a few neutron energies. Over the energy range from about 20 keV to 4.5 MeV calibrations were obtained using a variety of isotopic neutron sources. D-D and D-T neutrons provided points at 2.5 and 14 MeV. By removing the cadmium shield the moderator could be exposed to the thermal column of a nuclear reactor and the thermal neutron response measured. The thermal neutron response is about the same as the 2 MeV response(14,15). *In toto* these measurements suggest that "-- *the thermal-*

*neutron flux detected ---(at the center of the moderator) ---by the (activation) detector is also nearly proportional to the incident fast neutron flux in the energy range from 0.02 keV to 20 MeV*"[12]. Gilbert *et al.*[16] and Shaw *et al.*[17] have reported studies of the accuracy of dose equivalent determinations using only Smith-Stephens detectors in the broad energy spectra typical of high-energy accelerators. These studies suggest that, in unknown energy spectra, in extreme cases, the dose equivalent might be uncertain by as much as a factor of 3 or more. However, if the spectrum is known the dose equivalent may be determined with an uncertainty of about ±30% or better by the selection of an appropriate conversion coefficient.

Calculations by *Donahue et al.*[18] using the tabulations of response functions for a $^{6}$LiF thermoluminescence dosimeter/6" (15.2 cm) diameter spherical moderator combination given in IAEA Technical Report 318[19,20] conclude that "--*if the detector were calibrated to a known dose equivalent produced by the $^{239}$PuBe source but irradiated in the neutron energy spectrum at the Olympus Gate EMS, the dose equivalent due to Bevatron operation would be overestimated by about 30%".* The conversion coefficient data were taken from ICRP Publication 21 but the conclusion is not strongly dependent upon the particular set of coefficients used. This conclusion suggests that the calibration of the Smith detectors used at LBNL provided a comfortable but not excessive overestimate of neutron fluence for the typical neutron spectra discussed in this paper.

From the outset of operations measurements to characterise and quantify the radiation environment of the Bevatron were made both in occupied areas within the laboratory, around the laboratory perimeter and at some locations off-site. The neutron fluence at a distance of more than about 100 meters from the Bevatron was shown to approximately obey the inverse square law[21] but with the suggestion that *"-------most of the data from the present measurements appears to follow lines having a slightly steeper slope than would result from a purely inverse-square dependence*."[22] The identification of those locations at the site boundary where the radiation levels from the laboratory's accelerators were highest provided the foundation for a routine environmental radiation-monitoring program, [see, for example, reference[2]].

**THE RADIATION FIELD OF THE BEVATRON**

Neutrons dominated the radiation field around the Bevatron[21]. In the early years the shield leakage spectrum was rich in intermediate-energy neutrons. The resulting close-in radiation field was relatively "soft" and it was found that materials with high water (hydrogen content) provided excellent shielding. On the basis of *linear thickness* wood and concrete were found to be roughly equivalent: this phenomenon was observed at many early accelerators where steel was used, either intrinsically or extrinsically, for shielding.

Limited information on the energy spectrum of neutrons outside shielding was available in the early days of Bevatron operation. Systematic studies, in the late 1950's and early 1960's, of high-energy accelerator radiation environments led to the conclusion, by using the conversion coefficient data then available, that at that time neutrons with energies below 20 MeV contributed 80%–90% of the total dose equivalent. Neutrons with energies greater than 50 MeV and gamma rays each contributed a few percent of the total dose equivalent[6,8,12,21-25]. Patterson *et al.*[26,27] showed these results to be generally consistent with those obtained for the equilibrium neutron spectrum generated by the interaction of primary cosmic-ray protons with the Earth's atmosphere.

Because photons contributed only a small fraction of the total dose equivalent this paper focusses on the dose equivalent produced by neutrons.

## BEVATRON NEUTRON SPECTRA I: THE HISTORICAL SPECTRA.

**Late 1950s-mid 1960s.** The equilibrium neutron spectrum generated by the interaction of primary cosmic-ray protons with the Earth's atmosphere measured by Hess *et al.*[26] was used to interpret and substantiate the early neutron measurements at the Bevatron.

Figure 2 shows the Hess cosmic ray neutron energy spectrum and the spectrum outside the concrete shielding of the Bevatron, which was determined some years after the work of Hess *et al.*[16,26]. The Hess spectrum would have closely resembled the Bevatron spectrum at large distances from the accelerator, after the "hardening" of the close-in spectrum, rich in intermediate-energy neutrons, by interaction in the air had occurred. Patterson describes measurements made in the early 60s that demonstrate such spectrum-hardening[21]. Calculations showing spectrum-hardening in the air are described later in this paper in the section entitled "Skyshine and the Variation of Dose Equivalent with Distance".

There is a general similarity between the Hess Cosmic Ray and Shielded Bevatron spectra of figure 2 but their differences are revealed by a lethargy plot, [($E(d\phi/dE)$], as function of neutron energy in linear-log fashion [see footnote 6]. Differences in structure in the few hundred keV to few tens of MeV energy region may be seen. The shift to higher energies seen in the broad "hump" of the shielded Bevatron spectrum, compared with that of the Hess spectrum, may be qualitatively explained by the removal of intermediate energy neutrons leaking from the steel magnet yoke of the synchrotron by the concrete shield *i.e*. that the presence of roof shielding has "hardened" the neutron spectrum. This is consistent with our understanding of the performance of neutron shields [see, for example, Chilton *et al*.[(28)]].

For comparison figure 2 also shows a simulated energy-spectrum in air at the Olympus Gate Environmental Monitoring Station made with a bare thick copper target. The calculation of this spectrum will be discussed later in the section entitled "Bevatron Neutron Spectra III: distant (environmental) spectra".

The good qualitative agreement between the Hess Comic ray spectrum and calculated bare target spectrum in air was not entirely unexpected. However, the agreement of the <g> values to within about 10% is remarkable and is discussed later in the section on spectrum-weighted conversion coefficients. The energy spectrum calculated by Donahue *et al*. is somewhat "softer" than the Hess Cosmic Ray spectrum that was used as a paradigm for the neutron energy-spectrum produced around the early Bevatron before the shielding-roof was constructed.

Because of the presence of iron-leakage neutrons already mentioned it is most likely that in the early days of Bevatron operation the neutron energy-spectrum more closely resembled the cosmic-ray energy-spectrum than did the shielded Bevatron energy-spectrum. The neutron spectra determined in the early 60s were obtained by the application of physical and mathematical principles to the data obtained from a small number of detectors and were consequently of limited energy resolution. Nevertheless, analysis suggested that such spectra would give reliable estimates of dose equivalent and that conclusion has been confirmed by the work reported here.

**BEVATRON NEUTRON SPECTRA II: SOURCE AND CLOSE-IN SPECTRA**.

**Simulation Model.** In the work reported here, an independent assessment was made using current radiation transport computer codes to simulate the characteristics of the neutron source produced by the Bevatron. Transport calculations then determined the neutron energy spectrum at locations at the laboratory boundary. These calculations were performed using the MCNPX code that is a newly released combination of the low energy MCNP code with the high energy LAHET code [29]. The calculations are described in detail by Donahue *et al*.[18].

The calculations proceeded in three steps:

- Determination of the initial source terms - the energy spectra of neutrons produced at the Bevatron for three cases by protons incident on a thick copper target with and without overhead shielding.
- Transport of the initial source neutrons through the atmosphere to the location of the Olympus Gate EMS.
- Conversion of the fluence spectra thus calculated to dose equivalent using both the historical conversion coefficients and a more appropriate set of conversion coefficients derived from current data.

**Bevatron Source Spectra.** The primary neutron source was modelled by a 6.2 GeV beam of protons striking a 30 cm thick block of copper. This model was representative of the eventual loss of the accelerated protons to the wall of the vacuum chamber and subsequently in the iron yoke of the magnets. Neutrons are produced mainly via spallation and fragmentation reactions with the target (iron/copper) nuclei and subsequent evaporation processes from the residual excited nuclei. The resulting neutron energy-spectrum is strongly dependent on angle as measured with respect to the direction of the incident beam. In general, the higher the energy of the spallation neutrons the more forward they are directed. Evaporation neutrons are emitted isotropically.

Figure 3 shows two calculated source energy-spectra, the first at 0° to the beam direction (indicated by squares) and the second at 90° to the beam direction (indicated by diamonds). The spectrum is much harder (energetic) at 0°, extending up to approximately the incident proton energy. The evaporation peak, which has a maximum at about 1 MeV and extends to about 15 MeV, is clearly evident. The total neutron yield is dominated by the evaporation peak. The spectrum at 90° to the beam direction is appropriate for calculations of neutron energy-spectra at the site perimeter.

**Simulated Close-in Bevatron Spectrum.** In the early days of operation neutron leakage through the magnet yoke and pole tips determined the Bevatron neutron energy-spectrum close to the accelerator. This spectrum may be calculated by transporting the neutrons emitted by the primary radiation source through steel. It has been estimated that the thickness of the magnet iron yoke and magnet pole tips above the locations of proton beam loss was between 42 and 66 inches [1.07 and 1.67 m][8,30]. The calculation of the steel leakage spectrum was performed by a computer simulation in which thickness of 1 m of iron was added above the proton beam target. The neutron energy-spectrum was tallied and compared with the case without iron shielding. This comparison is shown in figure 4.

A similar calculation was made with 1 m of concrete ($\rho = 2.4$ g cm$^{-3}$) above a thick copper target bombarded by protons. In this case, when normalised to an integral of 1.0, the concrete-shielded and bare target spectra appear to be almost identical, with the exception of the energy region of the spallation shoulder, around 75-125 MeV, where the concrete spectrum has slightly more fluence than does the bare target spectrum.

The iron-shielded spectrum is shown as the dotted histogram. It may be seen that the iron-shielded spectrum close to the primary target is softer (lower in energy) than the unshielded spectrum, and contains structure at energies indicative of nearby resonances in the iron cross section. This result was not unexpected and is in agreement with the many observations reported in the literature of "soft" energy spectra leaking from iron shields (see Patterson[8]).

## BEVATRON NEUTRON SPECTRA III: DISTANT (ENVIRONMENTAL) SPECTRA.

**Simulation Model**: To determine the neutron energy-spectra at the Olympus Gate a simulation was set up by placing a point isotropic neutron source, with the appropriate primary source spectrum (thick Cu target, at 90°, bare or either with 1 m concrete or 1 m steel overhead shielding), at the centre of a hemisphere of air. Neutrons were transported from the source to the location of the Olympus Gate EMS [427 metres (1400 feet) laterally from and 122 metres (400 feet) in elevation above the Bevatron, corresponding to a line of sight distance 444 metres (1457 feet)]. The neutron fluence was determined by tallying neutrons that reached this location both directly (line-of-sight) and by scattering in the atmosphere. Three cases were run: with a bare target, with 1m of steel above the target and with 1m of concrete above the target.

Some preliminary calculations were necessary to enable the simulation model to be specified with adequate precision. The modelled atmosphere required a radius of at least 1 km (approximately 120 g cm$^{-2}$) to enable the scattered neutron component to attain its full value. Subsequent calculations reported here used a value of 3 km for the radius of the atmospheric hemisphere. Several simulations were run varying the relative humidity of air. As expected, the neutron fluence or dose equivalent at OGEMS was independent of the relative humidity. (Even at high relative humidity the moisture content in the air amounts to less than 0.2% hydrogen by weight).

**Simulated Bevatron Spectrum in air at the Olympus Gate.** Figure 5 shows computer energy-spectra at the location of OGEMS using two primary source spectra (i) a bare thick copper target bombarded by 6.2 GeV protons, and (ii) a similar copper target but with 1 m of steel overhead shielding placed above it. It was important to determine if the influence of the intrinsic shielding of the steel magnet yoke on the Bevatron close-in neutron spectrum (already described - see figure 4) persisted at large distances the Olympus Gate EMS. A calculation of the neutron energy spectrum in air at OGEMS for the case of a concrete-shielded target is not shown in figure 5 because it is so similar to the bare target spectrum. (see also the section on the influence of the ground and on spectrum-weighted conversion coefficients).

A comparison of the neutron energy-spectra shown in figures 4 and 5 shows that the neutron energy-spectrum at OGEMS calculated using an iron-shielded copper target as the primary target retains some of the characteristics seen in the shielded target spectrum of figure 4. The iron-shielded target spectrum is generally softer than the unshielded target spectrum, with a lower dose equivalent per unit fluence. Air-scattering has reduced the significance of the neutrons in the 20 keV region of the spectrum at OGEMS when compared with the source spectrum. As will be shown later, the dose equivalent per unit fluence for the steel-shielded source is about half that for the unshielded copper target.

**Influence of the ground on the simulated spectrum at the Olympus Gate.** Scattering of neutrons by the ground affects the shape of the fluence and dose equivalent energy spectra. The largest influence on spectrum shape is neutron energy moderation, largely by the hydrogen present in the soil (mainly in the form of water). To determine the magnitude and character of this influence a simulation was performed by modelling the earth at the location of Olympus Gate EMS with a cylinder 20 meters in radius and 1 meter thick placed below the tally point. The cylinder consisted of soil with water content of 30% by weight (a value at the high end of the typical range) and located at the Olympus Gate EMS. The source term used was an unshielded, thick copper target. The resulting neutron energy-spectra, with and without the soil column, are shown in figure 6. The soil column (ground scatter) produced a small but statistically significant increase in the low energy fluence at energies below about 0.1 keV but the corresponding increase in the total fluence is very small and the dose equivalent per source neutron is essentially unchanged.

The OGEMS neutron-energy spectra calculated with a bare copper target and with a concrete shielded target, both with earth under the detector, are almost identical and have identical <g> values. In the case of the steel shielded target, with the source already rich in low-energy neutrons, the influence of the presence of earth on the <g> value is indiscernible. (See the discussion in the section on spectrum-weighted conversion coefficients).

**FLUENCE TO EFFECTIVE DOSE CONVERSION COEFFICIENTS**

Increasing sophistication in radiobiological and anatomical modelling has led to changes in the definition of dose equivalent quantities, and they have been given different names [*viz.* Dose Equivalent (1964)[25], Effective Dose Equivalent (1977)[31,32] and Effective Dose (1991)[33]]. Although there are subtle differences between these quantities the corresponding neutron fluence to dose equivalent quantities have remained remarkably stable. In a review of conversion coefficients for AP irradiation geometry (see footnote 7) McDonald *et al*. commented: "*Over the years, a number of changes have taken place that affect the neutron fluence to dose equivalent conversion coefficients. Quality factors and reference phantoms have been changed. Radiological data, such as stopping powers, have become better known, and physics calculations have been improved. In addition new radiation protection quantities have been defined. ---- However, ----the conversion coefficients have been nearly invariant.*"[34]

In 1997/8 the ICRP and ICRU recommended a set of specific values for neutron fluence to Effective Dose conversion coefficients for energies up to 180 MeV. These coefficients are been tabulated in ICRP Publication 74 and ICRU Report 57 for the standard ICRP/ICRU geometries (see footnote 7)[35,36]. These ICRP/ICRU recommendations were based on a literature-wide review and incorporate seven independent studies and are plotted in figure 7 which shows the dependence of the value of the conversion coefficients on irradiation geometry. In the eV and keV energy region the values for AP geometry are always at least twice as large as those for ISO geometry and can be as much as three times larger. Between about 1 MeV and 20 MeV this ratio declines from 2.4 to 1.4. Above 20 MeV the curves for all irradiation geometries begin to converge and are nearly equal at 180 MeV.

Practical considerations of potential exposures of persons near accelerators lead to the conclusion that the ISO irradiation geometry is the most appropriate for calculations of dose equivalent in areas surrounding particle accelerator facilities. The radiation field outside accelerator shielding is typically produced by many diffuse sources. Furthermore, the preponderance of the dose is deposited by relatively low-energy neutrons, which are scattered (approximately) isotropically by the air, and by surrounding structures. Typically the normal activities of people present in the radiation field (such as walking, sitting, sleeping) will result in their quasi-random orientation with respect to the incident radiation and leads to the conclusion that their exposure will be isotropic in character.

Figure 7 shows that the application of conversion coefficients derived for AP irradiation geometry to exposure in isotropic irradiation conditions will overestimate the dose equivalent produced by the broad neutron spectra typical of the Bevatron. This was confirmed in a preliminary reappraisal of the reported dose equivalents during the early days of Bevatron operation by Thomas *et al*. who suggested that "----*the dose equivalents reported in the late fifties and early sixties were conservative by factors between two and four. In any current review of the historical data, therefore it would be prudent to reduce the reported dose equivalents by at least a factor of two*."(1)

In the fifties and sixties the conversion of the measurements of neutron fluence to dose equivalent was constrained because the only available data were for AP irradiation geometry. For example, in 1965 Thomas published a set of analytical functions that summarised available conversion coefficient data (only for AP irradiation geometry) at that time(37). In the eighties the ICRU defined the concepts of expansion and alignment and, with the adoption of the conventional ICRP/ICRU irradiation geometries and the development of anthropomorphic phantoms, it became possible to calculate conversion coefficients appropriate to broad neutron radiation fields such as these around particle accelerators(38,39). ICRP Publication 51 (1987) gave limited conversion coefficient data in these conventional irradiation geometries(40) and now more extensive data are available in ICRP Publication 74/ICRU Report 57(35,36).

One vital aspect of the work reported here, then, was the selection of conversion coefficients appropriate to accelerator environmental radiation fields. Thomas and Zeman(41) have described the procedure used for the selection of the conversion coefficients for ISO/ROT irradiation geometry used in the studies reported here. Since 1996 Ferrari *et al*.(42) and Yoshizawa *et al*.(43) have published other data, not available to the joint ICRP/ICRU Task Group that prepared ICRU Report 57. Their work is primarily devoted to the extension of conversion coefficients to high-energies (in the GeV region and above). Ferrari *et al*. give data for PA, AP, LAT and ISO irradiation geometries. Yoshizawa *et al*. give data only for AP and PA irradiation geometries.

At energies below 200 MeV heavy reliance was placed upon the ICRP/ICRU coefficients of ICRU Report 57 in selecting data for a new conversion function, to replace the AP data of the sixties. This was done, not only because of their international acceptance but also because they are based upon a critical review of seven sets quasi-independent calculations, while only limited data for ISO and ROT irradiation geometry are provided by Ferrari *et al*. below 200 MeV. However, ICRU Report 57 does not provide values for conversion coefficients in ISO geometry beyond an energy of 20 MeV but values of ROT coefficients are given up to 180 MeV. The ROT conversion coefficients are consistently largely than the ISO coefficients but at about 50 MeV the conversion coefficients for all irradiation geometries begin to converge and are about the same at 180 MeV. This confluence makes it possible to achieve a smooth transition between the ISO and ROT irradiation geometry data. (for more details see reference(41).)

At energies above 200 MeV, there are differences between the two sets of data of Ferrari *et al.* and Yoshizawa *et al.* that are larger than would be expected from the statistical precision of the calculations (about ±4% or less). The possibility of some systematic error needs to be examined but is beyond the scope of this paper. Differences can arise from specific details of the transport codes and phantoms. Ferrari *et al* state *"----differences of 5% can be expected among the results of proven codes*" (42) [see also Pelliccioni and Pillon(44) who discuss the influence of phantoms]. In the absence of a complete understanding of these variations between these two data sets, and the absence of any clear and obvious pattern, the data were pooled. Ideally, one would wish for more precise data in this energy region above 200 MeV but it is fortunate that the impact of any uncertainty in the conversion coefficients in this energy range is lessened by the relatively small contribution to the dose equivalent (~20%). Thus, for example, a 10% error in the coefficients will be reflected as an uncertainty of about 2% in the dose equivalent computed over the entire energy range of the neutron spectrum.

**Analytical Representations of Conversion Functions**. Tabulated conversion coefficients may be conveniently summarised by analytical functions(37,45,46). Such a representation has advantages for numerical manipulation.

The energy range of the neutron spectrum may be derived by considering it to be composed of k energy regions in each of which g(E) may be expressed by the exponential form $aE^m$. Thus in the jth energy region, bounded by the energies $E_j$ and $E_{j+i}$:

$$g_j(E) = a_j E^{m_j} \qquad E_j < E \leq_{j+1} \qquad (3)$$

and the complete function may be expressed by the sum of all such $g_j$s:

$$g(E) = \sum_{j=1}^{j=k} a_j E^{m_j} \qquad (4)$$

This procedure was followed by Thomas in 1965 to represent the conversion coefficient data available for AP irradiation geometry at that time(37). The energy range from $2.5 \times 10^{-8}$ to $6 \times 10^{3}$ MeV was conveniently divided into four discrete energy regions and best fits to the available data obtained. Table 1 summarises the values of the coefficients $a_j$ and $m_j$, obtained by the fitting procedure, from which values of the coefficients g(E), in units of in pSv $cm^2$, may be calculated, when E is in MeV. This analytical conversion function is denoted in this paper by RHT-1965 and is plotted in figure 8.

The conversion coefficients of RHT-1965 had an impact on the recommendations of the ICRP in Publication 21(20) and in a recent review McDonald *et al*.(34) showed that the function RHT-1965 remains a good approximation to tabulated values of conversion coefficients for AP irradiation geometry.

The data selected for the development of analytical functions for ISO irradiation geometry, consisting of data from ICRU Report 57 and pooled data of Ferrari *et al*. and. and Yoshizawa *et al*., have already been described. Inspection of all the conversion coefficients for ISO and ROT irradiation geometries suggested that the energy range from $2.5 \times 10^{-8}$ to $6 \times 10^{3}$ MeV may be conveniently divided into five discrete energy regions. Values of the coefficients $a_j$ and $m_j$ were determined so as to replicate the primary data as closely as possible, while avoiding serious discontinuities at the boundaries of the energy regions table 2 summarises the values of the coefficients $a_j$ and $m_j$, and the region energy limits $E_j$ and $E_{j+1}$, from which values of the coefficients g(E), in units of in pSv.$cm^2$, may be calculated, when E is in MeV. This analytical conversion function is denoted in this paper by DSTZ-2000 and is plotted in figure 8 together with the function RHT-1965. The ratio of the values of the two sets of coefficients as a function of energy is also shown.

These analytical functions typically represent the basic data with a standard deviation of ± few % over the greater part of the energy regions but sometimes with differences of more than 10% at the extremes of the energy region. Details are given in reference[41]. Sample calculations with the Hess Spectrum and the Shielded Bevatron Spectrum show agreement to better than ±5% using either the analytical expressions or the tabulated conversion coefficients from which the analytical expressions are derived. As a check on the conversion function data and the integration procedure used in this work the earlier estimates of <g> obtained by Gilbert *et al.*[16] were replicated[1].

**SPECTRUM-WEIGHTED CONVERSION COEFFICIENTS**

In the late fifties and early sixties, values of spectrum-weighted conversion coefficients, <*g*>, [as defined in equation (2)] were inferred both from inspection of the NBS and ICRP data at the measured values of the average (effective) energy of the neutron spectra [6,21,25] and by the assumption that the neutron spectrum at large distances from the Bevatron would be similar to the Hess cosmic-ray neutron spectrum[26,27]. By such means the Berkeley Health Physics group derived values of <*g*> in 1960 of 360 pSv.cm$^2$[47] and 370 pSv.cm$^2$ in 1962[22] [corresponding to an effective neutron energy of about 1 MeV - see NBS Handbook 62].

A value of <g> = 408 pSv.cm$^2$ was used in environmental radiation-monitoring reports published in the early and mid-sixties[48], after some information on the shielded Bevatron neutron spectrum was available. At the time that these estimates of <*g*> were obtained it was understood that the conditions selected for their derivation were conservative, particularly because of the irradiation geometry used to calculate the conversion coefficients in references 6 and 25. For his estimates of shielding for the Bevatron Improvement Program, Moyer adopted an even greater degree of conservatism by using a value of 1000 pSv cm$^2$ for <*g*>[3-5].

From Equation 2 it is apparent that more reliable estimates of <*g*> are possible if both $g_G(E)$ and $d\phi/dE$ are known. Previous sections have described the derivation of both these elements and it was therefore possible to calculate values of <g> both for the historical spectra and for the simulated spectra at OGEMS.

Table 3 summarises a total of 18 values of spectrum-weighted conversion coefficients, 3 in early use at the Berkeley Laboratory, 1 used for shielding calculations and the remaining 14 values calculated from equation (2). Of these 14 values 4 are for the historical spectra and 10 are for the simulated spectra at OGEMS.

The 10 calculated values of <g> for the OGEMS spectra are made with:

- Two conversion functions (RHT-1965 and DSTZ-2000)
- Three primary sources (bare Cu target, 1 m steel shielded Cu target and 1 m concrete shielded Cu target)
- In air and with earth below the detector

Inspection of the ratios of the <g> values is informative. For example the ratios $[\langle g\rangle_{\mathrm{RHT\text{-}1965}}/\langle g\rangle_{\mathrm{DSTZ\text{-}2000}}]$ show that application ISO conversion coefficients reduces the dose equivalent per unit fluence by a factor of slightly more than 2 compared with the use of AP conversion coefficients.

As expected, the moderating influence of the ground water is seen to be smaller for neutron energy-spectra rich in intermediate energy neutrons (*e.g.* steel leakage spectra) than is the case for spectra relatively richer in neutrons in the MeV energy region (*e.g*. bare and concrete shielded copper target). The ratios $[\langle g\rangle_{\mathrm{air}}/\langle g\rangle_{\mathrm{ground}}]$ show that in the case of the bare copper target the ground reduces the dose equivalent per unit fluence by a factor of about 1.4 when compared with the air. For the steel shielded spectrum this reduction factor is increased to 2.2.

The influence of the magnet yoke determined from the ratios of $[\langle g\rangle_{\mathrm{bare\ target}}/\langle g\rangle_{\mathrm{Fe\ shielded\ target}}]$ show that the influence of the magnet yoke is to reduce the dose equivalent per unit fluence for the spectrum in air also by a factor of about 2.1. However, it is important to emphasise that these effects are not necessarily multiplicative. For example, the combined influence of the magnet yoke and the ground is to reduce the dose equivalent per unit fluence by an unchanged factor of about 2.2.

The data of table 3 show that the values of <g> used in Berkeley in the 60s are larger than those calculated for the two "historical spectra", which are in turn larger than those determined for the simulated spectra. Thus the general conclusions of Thomas *et al*. are confirmed but with the degree of overestimation somewhat greater than their suggested value of "between two and four"(1).

Selecting from table 3 only values for the simulated OGEMS spectra calculated using isotropic irradiation geometry with the latest conversion function DSTZ-2000 and taking the value of <g> used at LBNL in the 60s to be 360 pSv cm$^2$, the range of overestimation is between 5.5 and 8.4. It is prudent to conclude that the dose equivalents reported in the early sixties could be reduced by a least a factor of at least five using current methods of analysis.

**SKYSHINE AND THE VARIATION OF DOSE EQUIVALENT WITH DISTANCE.**

Insight into the decrease in dose equivalent with distance was obtained by computer simulations that calculated the neutron dose equivalent energy-spectrum at distances of 100, 300 and 600 m from the Bevatron [Donahue *et al*.[18]]. Figure 9 shows the dose equivalent spectra calculated at these three distances. The error bars indicate the statistical uncertainty of the calculated values. These spectra are normalised so that the total area under each curve is 1.0. It can be seen that the spectral shapes are not identical and that the energy spectrum becomes harder with increasing distance as the low energy evaporation neutrons emitted by the source are preferentially attenuated in air. Figure 9 explains the observed increase in average energy of the neutron spectrum with distance from the Bevatron[21].

As early as 1962 Dakin, in summarising early neutron measurements at the Bevatron, had reported in describing a number of plots showing measured neutron fluences at various distances and for various compass quadrants relative to the Bevatron that: -------*most of the data from the present measurements appears to follow lines having a slightly steeper slope than would result from a purely inverse-square dependence*[22].

The Bevatron is partially surrounded by a steep hillside with houses located at or near its crest and beyond. The Olympus Gate EMS is located near the crest of this hillside, in sight of, and approximately 427 metres horizontally and 122 metres vertically from the centre of the Bevatron. The total neutron fluence measured at the Olympus Gate EMS, in direct line-of sight, represents the maximum to which any member of the general public could be exposed due to Bevatron operations. The measured fluence consisted of both neutrons that had directly emerged from the roof of the Bevatron building and from neutrons scattered by the atmosphere down to Earth.

Most houses near the Bevatron are beyond the crest of the hill and not in the direct line-of-sight to the Bevatron. Therefore any neutrons reaching those houses were the result of skyshine [large-angle scattering by the atmosphere[49,50].] and the neutron fluence was correspondingly reduced. Measurements by McCaslin[51] suggest that, at the same distance from the Bevatron, neutron fluence rates were lower by a factor of about 1.8 when hills intervened. It is possible to check this conclusion by computer simulations.

Computer simulations of the variation of dose equivalent with distance from the Bevatron also confirm the early observation of Dakin and Patterson by showing that both total dose equivalent, (due to both uncollided and collided radiation), and the contribution from neutrons that are transported directly from the source to the detector location without interaction (direct or uncollided component) decrease more rapidly than $[1/r^2]$[18]. At the Olympus Gate the collided fluence contributed about 75% of the total dose equivalent but it is important to distinguish between the collided component and what is usually referred to as "skyshine". In the calculations of Donahue *et al*. neutrons elastically scattered at very small angles are included in the tally for the uncollided component. Such a definition of uncollided radiation is too strict and underestimates "skyshine", which typically involves larger angle scattering[49,50].

An additional set of calculations was therefore necessary to estimate the relative dose equivalent rate due to skyshine alone (*e.g*. at houses beyond the hillcrest) and the following computer simulation was designed. A tally point was located at a distance of 444 meters from the Bevatron. A semi-infinite wall, 10 meters in height, was placed 10m. in front of the tally point. Any neutrons entering the wall were immediately terminated. Only neutrons scattered over the wall by the atmosphere were allowed to contribute to the neutron fluence at the tally point. The computed dose equivalent at the tally point with the wall in place was then compared with the dose equivalent with no wall in place.

The result of these calculations was that the dose equivalent was reduced by a factor of about 2.5 (statistical error ±4%) below the dose equivalent observed without the wall in place (*c.f.* McCaslin's estimate for fluence of 1.8 with an estimated error of ±20%). One may conclude that the true skyshine contribution at Olympus Gate EMS is about half the total dose equivalent.

## SUMMARY AND CONCLUSIONS

The magnitude of dose equivalents produced in the late fifties and early sixties at the site boundary of the Lawrence Berkeley National Laboratory have recently been a matter of public scrutiny. The dose equivalents reported at that time were in compliance with contemporary radiation limits. They were also were known to be overestimates. It is has now become important that both the original radiation measurements be reviewed and their conversion to dose equivalent be reappraised using the best available information now available and the degree of conservatism, if any, determined. This paper summarises the reappraisal that is reported in greater detail in 3 separate internal LBNL reports[1,18,41].

In those early years of operation the reported dose equivalent, H, was derived from a measured total neutron fluence, Φ, and an estimated spectrum-weighted fluence to dose equivalent conversion coefficient, <g>, where:

$$H = \langle g \rangle \, \Phi$$

The techniques used to measure the total neutron fluence at that time at Berkeley were sufficiently accurate for the purpose intended and have subsequently been given international validation. The accuracy of the basic fluence measurements was not therefore the principal thrust of the work reported here. It is, however, important to comment that this work did show that the method of calibration of the primary detector used, by means of Pu-Be neutron source, provides a comfortable cushion when the detector is placed in "Bevatron-like" neutron fields (*e.g.* in the case studied it would have over-read by ~30%).

Information available in the 1950s and 1960s for estimating the spectrum-weighted fluence to dose equivalent conversion coefficient, <g>, was quite crude. It depended on measurements of average neutron energy, assumptions of the shape of the neutron energy spectrum and rather primitive values of fluence to dose equivalent conversion coefficients. This reappraisal therefore focussed on the determination of <g>, which required, in turn, the evaluation of neutron spectra and fluence to dose equivalent conversion coefficients for monoenergetic neutrons.

Neutron energy spectra at the location of the Olympus Gate Environmental Monitoring Station of the Lawrence Berkeley National Laboratory, were calculated by state of the art Monte Carlo simulation and radiation transport methods. Spectra were simulated to represent operating conditions of the Bevatron in the late 50s and early 60s, with the 6.2 GeV beam interacting in a thick copper target. Calculations were made with a bare target and a target with overhead shielding. The influence of air- and ground-scattering was taken into account. The simulated spectra were compared with the early assumptions about and estimates of the Bevatron environmental neutron spectra (*e.g.* see figure 2). In general the simulated spectra are "softer" than the paradigm of the Hess Cosmic Ray Spectrum used in the early years.

A new neutron fluence to dose equivalent conversion function was developed for this reappraisal. The complete conversion function consists of a set of four functions in analytical form covering the neutron energy range from 2.5 $10^{-8}$ to $10^{4}$ MeV. It was concluded that ISO irradiation geometry was most appropriate to describe typical irradiation conditions experienced around high-energy proton accelerators such as the Bevatron. (the early coefficients were limited to AP geometry). For neutron energies below 200 MeV the analytical functions were modelled after the ISO and ROT conversion coefficients in ICRU Report 57. For neutron energies above 200 MeV, the analytical function was derived from an analysis of recent published data of Ferrari *et al*. and Yoshizawa *et al*.

Values of spectrum-weighted fluence to dose equivalent conversion coefficients were calculated for these simulated spectra and compared with earlier assessments of <g>. Values of <g> from 360 - 408 pSv $cm^2$ were used at Berkeley in the sixties. These values are larger than those calculated for the two "historical spectra", which are in turn larger than those determined for the simulated spectra.

Taking the value of <g> used at LBNL in the 60s to be 360 pSv.$cm^2$ and considering only values for the simulated OGEMS spectra calculated using isotropic irradiation geometry the range of overestimation is between 5.5 and 8.4. It is prudent to conclude that the dose equivalents reported in the early sixties could be reduced by a factor of at least five using current methods of analysis. Thus the general conclusions of the preliminary appraisal [reference (1)] are confirmed but with a somewhat greater the degree of overestimation.

The dose equivalent at the site boundary represents an upper bound on the potential exposure to members of the public. More precise evaluation of potential exposure to people living near the laboratory boundary at that time would involve determination of several factors, including times and duration of occupancy, influence of the inverse square law, the shadowing effects of hills, and the shielding provided by houses.

Two of these factors have been studied in this report. Calculations of the decrease in neutron fluence with distance are in agreement with earlier studies. It was shown that radiation levels at places not in direct view of the Bevatron were reduced by a factor of 2 (*i.e.* for location in direct view of the Bevatron the line-of-sight and skyshine contributions are about equal).

**Acknowledgements**

The authors wish to thank Dr. Edward J. Lofgren, Associate Director Emeritus, for helpful discussions about the early days of Bevatron operations.

This work was supported by the Director, Office of Science, Office of Basic Energy Sciences, of the U. S. Department of Energy, under Contract No. DE-AC03-76SF00098.

**References**

1. Thomas R. H, Smith, A. R. and Zeman, G. H. *A Reappraisal of the Reported Dose Equivalents at the Boundary of the University of California Radiation Laboratory during the early Days of* Bevatron Operation. University of California, Lawrence Berkeley National Laboratory Internal Report, LBNL - 45224 (2000).

2. Thomas, R. H. [Ed.]. *The Environmental Surveillance Program of the Lawrence Berkeley Laboratory*, University of California Lawrence Berkeley Laboratory Internal Report, LBL-4678 (1976).

3. Moyer, B. J *Evaluation of Shielding Required for the Improved Bevatron*, University of California Radiation Laboratory Berkeley Internal Report, UCRL-9769 (1961).

4. Moyer, B. J. *Method of Calculation of the Shielding Enclosure for the Berkeley Bevatron*. Proceedings Premier Colloque International sur la Protection auprès des Grands Accélérateurs, [Editors: Bonet-Maury, P., Duhamel, M., and Perrin, F.], Paris, January 18-20, 1962, 65-70. Paris: Presses Universitaires de France (1962).

5. Thomas, R. H. *The Bevatron*. IAEA Engineering Compendium on Radiation Shielding [Editors. R. G. Jaeger *et al*.]. Vol. III, Section 10.7.3.1, 165-171. Berlin: Springer-Verlag (1970).

6. National Council on Radiation Protection and Measurements. *Protection against Neutron Radiation up to 30 MeV*. NBS Handbook 63. Gaithersburg, Maryland: National Bureau of Standards (1957).

7. United States Atomic Energy Commission. *USAEC Manual Chapter 0524 Manual of Feb. 1, 1958, Paragraph 0524-02*. (See also *Appendix AEC 0524-02-A*). Washington D. C: USAEC (1958).

8. Patterson, H. W. *Accelerator Radiation Monitoring and Shielding*. Proceedings of the First USAEC First Symposium on Accelerator Radiation Dosimetry and Experience, Brookhaven National Laboratory November 3-5, 1965. USAEC Conf- 651109, 3-18. Washington D. C: USAEC (1965).

9. National Council on Radiation Protection and Measurements. *Measurement of Neutron Flux and Spectra for Physical and Biological Applications*. NBS Handbook 72. Gaithersburg, Maryland: National Bureau of Standards (1960).

10. Moyer, B. J. *Survey Methods for Fast- and High-Energy Neutrons*. Nucleonics **10(5)**, 14–19, (1952).

11. Moyer, B. J. *Neutron Physics of Concern to the Biologist*. Radiation Research. **1**, 10–22, (1954).

12. Patterson, H. W., and Thomas, R. H. *Accelerator Health Physics.* New York: Academic Press (1973).

13. International Atomic Energy Agency. *Radiological Safety Aspects of the Operation of Proton Accelerators*. Technical Report No. 283. Vienna: IAEA (1988).

14. Stephens, L. D. and Smith, A. R. (1958). *Fast Neutron Surveys Using Indium Foil Activation*. University of California Lawrence Radiation Laboratory Internal Report, UCRL 8418 (1958).

15. Simpson, P. W. *The Measurement of Accelerator-produced Neutron Flux by Activation of Indium, Gold and Cobalt*. Rutherford Laboratory Internal Report, NIRL/M/70 (1964).

16. Gilbert, W. S., Keefe, D., McCaslin, J. B., Patterson, H. W., Smith, A. R., Stephens, L. D., Shaw, K. B., Stevenson, G. R., Thomas, R. H., Fortune, R. D. and Goebel, K. *1966 CERN-LRL-RHEL Shielding Experiment at the CERN Proton Synchrotron*. University of California, Lawrence Radiation Laboratory Report, UCRL-17941 (1968).

17. Shaw, K. B., Stevenson, G. R. and Thomas, R. H. *The Evaluation of Dose Equivalent from Neutron Energy Spectra.* Health Physics 1**7**, 459-469, (1969).

18. Donahue, R. J., Thomas. R. H. and Zeman, G. H. *Simulations of the Neutron Energy-spectra at the Olympus Gate Environmental Monitoring Station due to Historical Bevatron Operations*. Lawrence Berkeley National Laboratory, University of California Internal Report, LBNL-47422 (2001).

19. Griffith. R. V., Palfalvi, J and Madhvanath, U. *Compendium of Neutron Spectra and Detector Responses for Radiation Protection Purposes*. IAEA Technical Report No. 318. Vienna: International Atomic Energy Agency (1990).

20. International Commission on Radiological Protection. *Data for Protection against Ionizing Radiation from External Sources*. ICRP Publication 21. Oxford: Pergamon Press (1973).

21. Patterson, H. W. *The Effect of Shielding on Radiation Produced by the 730 MeV Synchrocyclotron and the 6.3 GeV Proton Synchrotron at the Lawrence Radiation Laboratory.* Proceedings of the Premier Colloque International sur la Protection auprès des Grands Accélérateurs [Editors: Bonet-Maury, P., Duhamel, M., and Perrin, F.], Paris, January 18-20, 1962, 95-99. Paris: Presses Universitaires de France (1962).

22. Dakin, H. S. and Patterson H. W. (1962). *Calculations of Integrated Gamma and Neutron Levels at the Nearest Continuously-Occupied Buildings at UCRL Berkeley Site Boundary for the Period January 1 to June 30, 1962*. Internal Memorandum, 13 July 1962. University of California Radiation Laboratory. (1962).

23. Patterson, H. W. *University of California Synchrocyclotron*. Proceedings of the Conference on Shielding High-Energy Accelerators, New York, 11-13 April 1957 (Editor L. Solon), USAEC Report TID-7545, 3-7. Washington D. C: USAEC (1957

24. Solon, L [Editor.] *Proceedings of the Conference on Shielding High-Energy Accelerators, New York, 11-13 April 1957*, USAEC Report TID-7545. Washington D. C: USAEC (1957)

25. International Commission on Radiological Protection. *Report of Committee IV on Protection Against Electromagnetic Radiation above 3 MeV and Electrons, Neutrons and Protons*, ICRP Publication 4. Oxford: Pergamon Press (1964) [see footnote 8].

26. Hess, W. N., Patterson, H. W., Wallace, R. W. and Chupp, E. L. *Cosmic Ray Produced Neutron Spectrum.* Phys. Rev. **116** (2), 445–457 (1959).

27. Patterson H. W., Hess, W. N., Moyer, B. J. and Wallace, R. W. *The Flux and Spectrum of Cosmic Ray Produced Neutrons as a Function of Altitude*. Health Physics **2**, 69 (1959).

28. Chilton, A. B., Shultis, J. K. and Faw, R. E. *Principles of Radiation Shielding*. New York: Prentice-Hall ISBN 0-13-709907-X (1984).

29. Los Alamos National Laboratory. *MCNPX, Version 2.1.5*. Los Alamos National Laboratory Internal Report LA-UR-99-1995. New Mexico: Los Alamos National Laboratory (1999).

30. Smith, A. R. Lawrence Berkeley National Laboratory, 20 November 2000, Private Communication. (2000).

31. International Commission on Radiological Protection. *Recommendations of the International Commission on Radiological Protection*, ICRP Publication 26. Annals of the ICRP, **1(3)** (reprinted with revisions, 1981). Oxford: Pergamon Press (1977).

32. International Commission on Radiological Protection. *Statement and Recommendations of the International Commission on Radiological Protection from its 1980 Stockholm Meeting*, ICRP Publication 30, Part 2. Annals of the ICRP **4 (3/4)**. Oxford: Pergamon Press (1980).

33. International Commission on Radiological Protection (1991). *Recommendations of the International Commission on Radiological Protection*, Publication 60. Annals of the ICRP **21(1–3)** Oxford: Pergamon Press (1991).

34. McDonald, J. C., Schwartz, R. B., and Thomas, R. H. *Neutron Dose Equivalent Conversion Coefficients Have Changed in the Last Forty Years—Haven't They?* Radiation Protection Dosimetry **78(2**), 147–149 (1998).

[See also Thomas, R. H. *The Impact of ICRP/ICRU Quantities on High-Energy Neutron Dosimetry - A Review*. Vylet, V. and Stevenson, G. R. (Editors). *Accelerator Radiation Protection*. Proceedings of the Tenth Course: Accelerator Radiation Protection, Ettore Majorana Centre for Scientific Culture, Erice, Sicily, Italy, 2-9 October Radiation Protection Dosimetry **96(4)**, xx-xx (2001)

35. International Commission on Radiological Protection *Conversion Coefficients for use in Radiological Protection against External Radiation.* ICRP Publication 74, Annals of the ICRP **26(3/4)** Oxford: Pergamon Press (1997).

36 International Commission on Radiation Units and Measurements. *Conversion Coefficients for use in Radiological Protection against External Radiation*, Report 57. Bethesda, Maryland: ICRU (1998).

37. Thomas, R. H. *The Radiation Field Observed around High-Energy Nuclear Accelerators*. Proceedings of the XI International Congress on Radiology, Rome, September 1965, 1849–1856. Amsterdam: Excerpta Medica Foundation (1967).

38. International Commission on Radiation Units and Measurements. *Determination of Dose Equivalents resulting from External Radiation Sources*, Report 39. Bethesda, Maryland: ICRU (1985).

39. International Commission on Radiation Units and Measurements. *Determination of Dose Equivalents resulting from External Radiation Sources-Part 2* , Report 43. Bethesda, Maryland: ICRU (1988).

40. International Commission on Radiological Protection. *Data for Protection Against Ionizing Radiation from External Sources*, ICRP Publication 51, Annals of the ICRP **17(2/3)**. Oxford: Pergamon Press (1987).

41. Thomas. R. H. and Zeman, G. H. *Fluence to Dose Equivalent Conversion Coefficients for Evaluation of Accelerator Radiation Environments*. University of California, Lawrence Berkeley National Laboratory Internal Report LBNL-47423 (2001).

42. Ferrari, A., Pelliccioni, M., and Pillon, M. *Fluence to Effective Dose Conversion Coefficients for Neutrons up to 10 TeV*. Radiation Protection Dosimetry **71(3**), 165-173 (1997).

43. Yoshizawa, N., Sato, O., Takagi, S., Furihata, S, Iwai, S., Takashi, U., Tanaka, S. and Sakamoto, Y. *External Radiation Conversion Coefficients using Radiation Weighting Factors and Quality factors for Neutrons and Protons from 20 MeV to 10 GeV*. Journal of Nuclear Science and Technology **35(12**), 928-942 (1998).

44. Pelliccioni, M., and Pillon, M. *Comparison between Anthropomorphic Mathematical phantoms using MCNP and FLUKA Codes*. Radiation Protection Dosimetry **67**, 253-256 (1996).

45. Rindi, A. *An Analytical Expression for the Neutron Flux-to-Dose Conversion Factor*. Health Physics **27,** 322-323 (1974).

46. Rindi, A. *An Analytical Expression for the Neutron Flux-to-Absorbed Dose Conversion Factor*. Health Physic **33**, 264-265 (1977).

47. Patterson, H. W. Internal Memorandum, 22 April 1960. University of California Lawrence Radiation Laboratory Internal Memorandum (1960).

48. Lawrence Berkeley Laboratory. *Environmental Radiation Measurements Made by the Health Physics Department for the Year 1964*, 15 February 1965. University of California, Lawrence Radiation Laboratory Internal Report (1965).

49. Rindi, A and Thomas, R. H. *Skyshine - A Paper Tiger?* Particle Accelerators **7**, 23-29 (1979).

50. Stapleton, G. B., O'Brien, K. and Thomas, R. H. *Accelerator Skyshine: Tyger, Tyger Burning Bright*. Particle Accelerators **44**, 1-15. (1994).

51. McCaslin, J. B. (1976). Lawrence Berkeley Laboratory. Private Communication, 1976, cited in reference[(2)] (1976).

## Footnotes

1. The University of California Radiation Laboratory has also been known as the Lawrence Berkeley Laboratory, the Lawrence Berkeley National Laboratory and is currently known as the Ernest Orlando Lawrence Berkeley National Laboratory. For brevity it is referred to as the Berkeley Laboratory or LBNL for the remainder of this paper.

2.The name is taken from Olympus Avenue, Berkeley that lies to the NE of the laboratory perimeter. Access to the laboratory is possible here via a gate through the perimeter fence (the Olympus Gate). One of the laboratory's several environmental monitoring stations is situated here and colloquially known as the Olympus Gate Environmental Monitoring Station, abbreviated to Olympus Gate EMS or OGEMS in this paper.

3. International Commission on Radiological Protection (ICRP).

4. National Council on Radiation Protection and Measurements (NCRP).

5. International Commission on Radiation Units and Measurements (ICRU).

6. The quantity $d(\phi)/d\log E = E\, d(\phi)/dE$ is called the lethargy spectrum by radiation physicists; it is widely used to describe such quantities as differential cross sections when a logarithmic scale is used on the horizontal axis. It has the advantage that if the vertical scale is linear, the area under the curve is the integral of $d(\phi)/dE$.

7. The conventional ICRP/ICRU geometries for the calculation of conversion coefficients in an anthropomorphic phantom are:

AP (antero-posterior): phantom irradiated from front to back.

PA (postero-anterior): phantom irradiated from back to front.

LAT (laterally): phantom irradiated from the side. (When necessary, calculations from the left and right sides of the phantom are designated by LLAT and RLAT)

ROT (rotationally): phantom irradiated while rotating about its longitudinal axis in the filed

ISO (isotropically) phantom irradiated isotropically

More precise definitions may be found in ICRU Report 57[36].

8. The information contained in ICRP Publication 4 was generally available to the accelerator community well before its publication in 1960.

# Tables

**Table 1**

**Coefficients for the Analytical Conversion Function RHT-1965 for A-P Irradiation Geometry***

| Energy Region | $E_j$ (MeV) | $E_{j+1}$ (MeV) | $a_j$ | $m_j$ |
|---|---|---|---|---|
| Region 1 | $2.5 \times 10^{-8}$ | $3.0 \times 10^{-2}$ | 12.0 | 0.00 |
| Region 2 | $3.0 \times 10^{-2}$ | $1.0 \times 10^{0}$ | 386 | 0.75 |
| Region 3 | $1.0 \times 10^{0}$ | $1.0 \times 10^{1}$ | 386 | 0.00 |
| Region 4 | $1.0 \times 10^{1}$ | $1\ 0 \times 10^{4}$ | 217 | 0.25 |

*The number of significant figures given is for the convenience of arithmetical manipulations only and does not indicate the accuracy with which these values are known.

**Table 2**

**Coefficients for the Analytical Conversion Function DSTZ-2000 for ISO/ROT Irradiation Geometry ***

| Energy Region | $E_j$ (MeV) | $E_{j+1}$ (MeV) | $a_j$ | $m_j$ |
|---|---|---|---|---|
| Region 1 | $2.5 \times 10^{-8}$ | $3.0.\times 10^{-6}$ | 29.0 | 0.121 |
| Region 2 | $3.0 \times 10^{-6}$ | $1.0 \times 10^{-2}$ | 6.44 | 0 |
| Region 3 | $1.0 \times 10^{-2}$ | $4.0 \times 10^{0}$ | 116 | 0.623 |
| Region 4 | $4.0 \times 10^{0}$ | $2\ 0 \times 10^{2}$ | 197 | 0.187 |
| Region 5 | $2.0 \times 10^{2}$ | $1.0 \times 10^{4}$ | 70.8 | 0.379 |

*The number of significant figures given is for the convenience of arithmetical manipulations only and does not indicate the accuracy with which these values are known.

**Table 3.**
**Summary of Values of Spectrum-weighted Conversion Coefficients**
**over the Energy Range $2.5x10^{-8}$ - $6.2x10^{3}$ MeV**

| Spectrum | Conversion Function | <g> (pSv.$cm^2$) | Comments | Reference |
|---|---|---|---|---|
| "Unshielded Bevatron" | Not applicable | 360 | NBS 63, ICRP 4, average energy measurement | Patterson 1960[47] |
| "Unshielded Bevatron" | Not applicable | 370 | NBS 63, ICRP 4, average energy measurement | Dakin & Patterson 1962[22] |
| Hess Cosmic-Ray Neutrons | RHT-1965 (AP) | 193 | "Historical Spectrum" | Thomas *et al*. 2000[1] |
| Hess Cosmic-Ray Neutrons | DSTZ-2000 (ISO) | 107 | "Historical Spectrum" | Thomas *et al*. 2000[1] |
| Shielded Bevatron | Not applicable | 1000 | Shield Design Only | Moyer 1961[3] |
| Shielded Bevatron | Not applicable | 408 | Routine use NBS 63, ICRP 4, average energy measurement | UCRL 1965[48] |
| Shielded Bevatron | RHT-1965 (AP) | 288 | "Historical Spectrum" | Thomas et al. 2000[1] |
| Shielded Bevatron | DSTZ-2000 (ISO) | 191 | "Historical Spectrum" | Thomas *et al*. 2000[1] |
| OGEMS, bare target, in air | RHT-1965 (AP) | 199 | Simulated Spectrum | This work |
| OGEMS, bare target, in air | DSTZ-2000 (ISO) | 94 | Simulated Spectrum | This work |
| OGEMS, bare target, with ground | RHT-1965 (AP) | 142 | Simulated Spectrum | This work |
| OGEMS, bare target, with ground | DSTZ-2000 (ISO) | 65 | Simulated Spectrum | This work |
| OGEMS, concrete shielded target, with ground. | RHT-1965 (AP) | 198 | Simulated Spectrum | This work |
| OGEMS, concrete shielded target, with ground. | DSTZ-2000 (ISO) | 95 | Simulated Spectrum | This work |
| OGEMS, steel shielded target, in air | RHT-1965 (AP) | 94 | Simulated Spectrum | This work |
| OGEMS, steel shielded target, in air | DSTZ-2000 (ISO) | 43 | Simulated Spectrum | This work |
| OGEMS, steel shielded target, with ground | RHT-1965 | 94 | Simulated Spectrum | This work |
| OGEMS, steel shielded target, with ground | DSTZ-2000 (ISO) | 43 | Simulated Spectrum | This work |

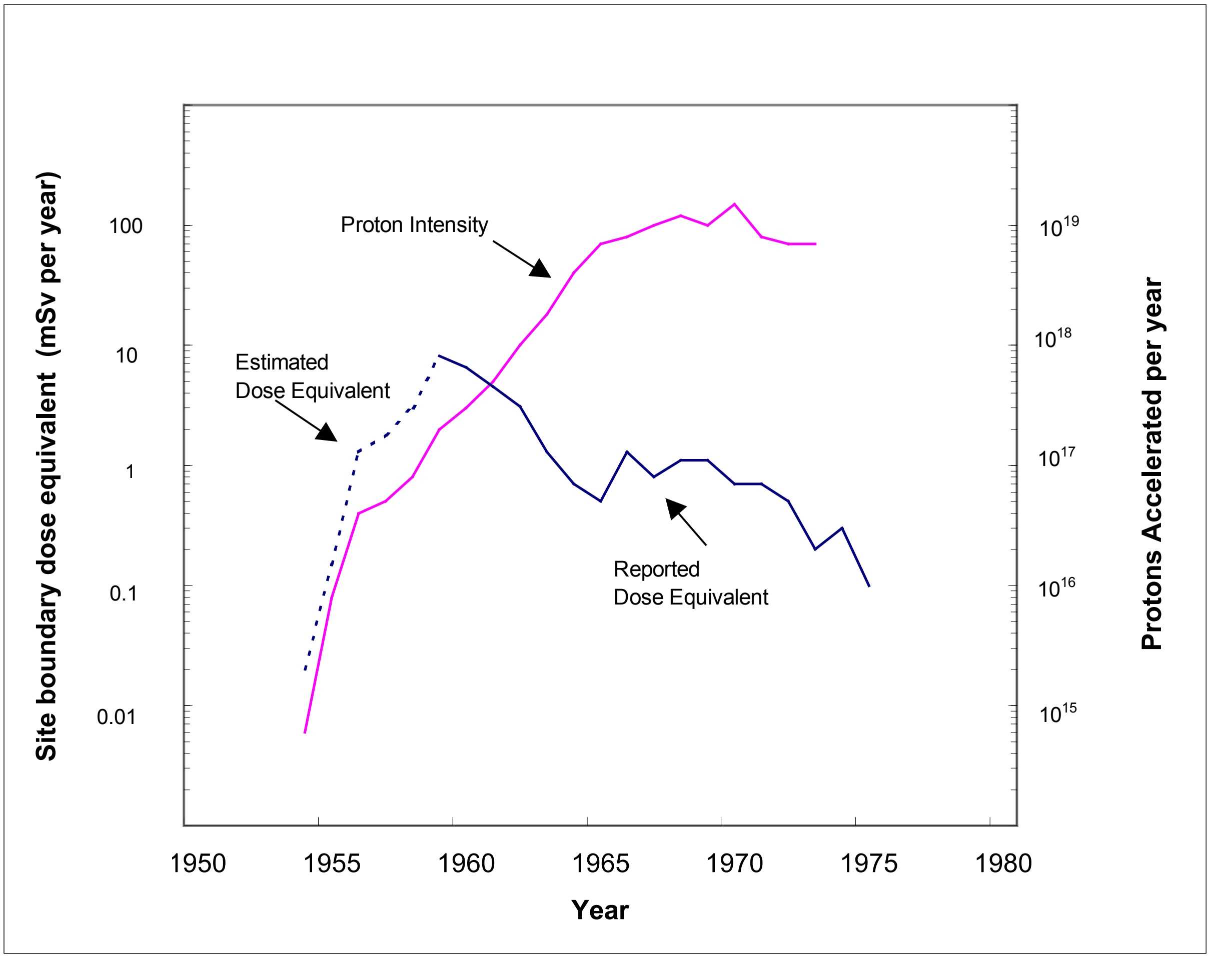


**Figure 1**

The dose equivalent reported at the Olympus Gate at the boundary of the Berkeley Laboratory during the period 1959-1973. The number of protons accelerated by the Bevatron per year during the period is also shown.

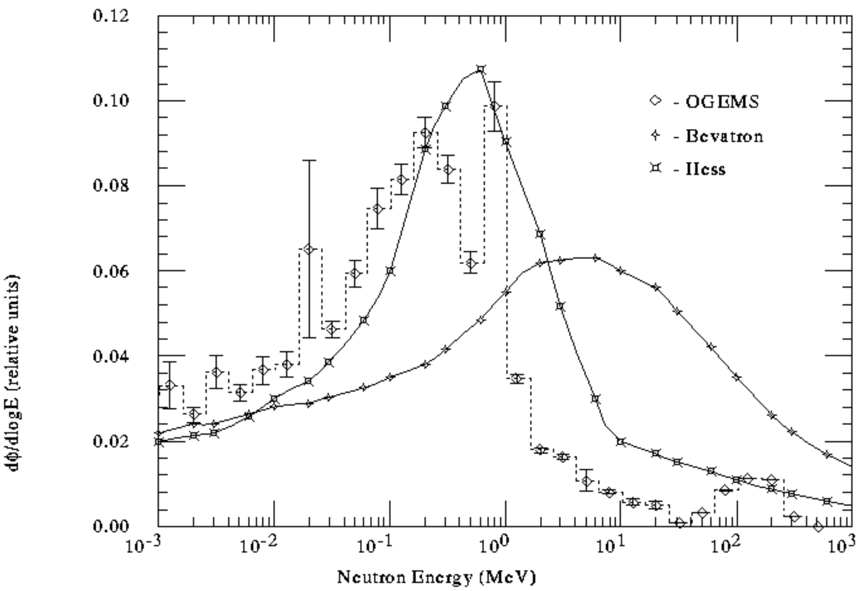


Figure 2

The differential energy spectrum per unit source neutron produced by the interaction of cosmic-ray protons in the Earth's atmosphere (Hess Cosmic-ray spectrum, circa 1958) compared with the spectrum outside the concrete shielding of the Bevatron (Shielded Bevatron spectrum, circa 1965). The simulated spectrum in air at the Olympus Gate Environmental Monitoring Station for a bare (unshielded) copper target is shown for comparison.

The spectra are presented in lethargy plot [(d(ϕ)/dlogE = E.d(ϕ)/dE] as a function of neutron energy [see footnote 6].

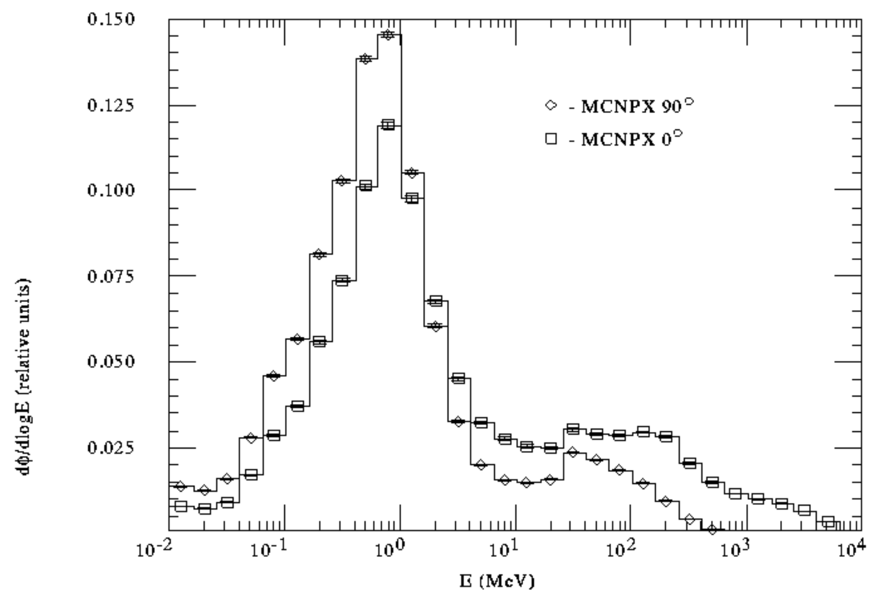


Figure 3

Neutron energy-spectra per unit source neutron produced by 6.3 GeV protons incident on a 30 cm. thick Cu target. Two spectra were calculated: the first at 0° to the beam direction (squares) and the second at 90° to the beam direction (diamonds). The spectra are presented in lethargy plot [(d(ϕ)/dlogE = E.d(ϕ)/dE] as a function of neutron energy [see footnote 6].

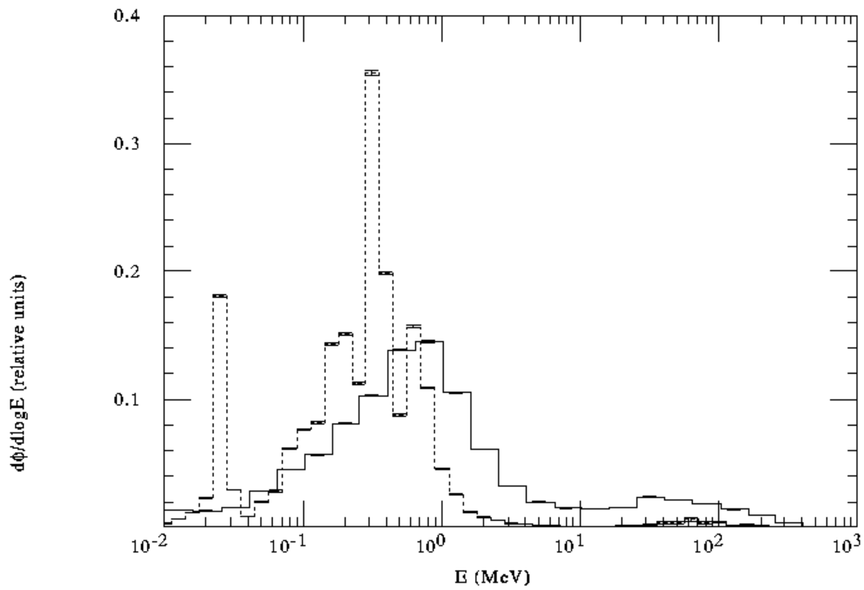


Figure 4

A comparison of two fluence energy spectra per unit source neutron at 90° to an unshielded shielded thick Cu target bombarded by 6.3 GeV protons. The solid-line histogram shows the neutron spectrum above an unshielded target (also presented in figure 3). The dotted histogram shows the spectrum with a thickness of 100 cm. of iron above the target. Both neutron energy-spectra are presented as a lethargy plot and normalised to an area of 1.0.

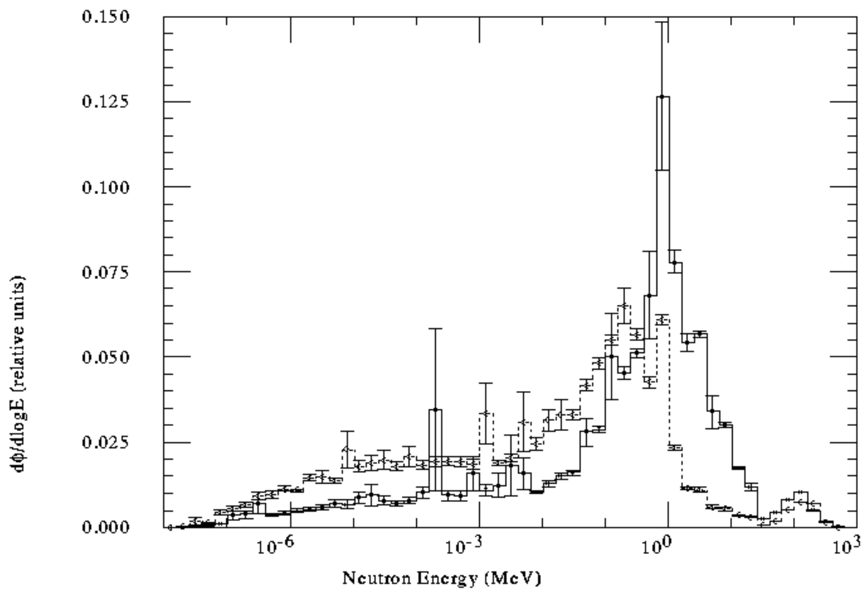


Figure 5

A comparison of the simulated neutron energy-spectra in air per unit source neutron at the Olympus Gate EMS resulting from a bare copper target bombarded by 6.2 GeV protons, located at the Bevatron, (a) with no overhead shielding (solid line) (dashed line) and (b) with 1 meter steel overhead. Both neutron energy-spectra are presented as a lethargy plot as a function of neutron energy.

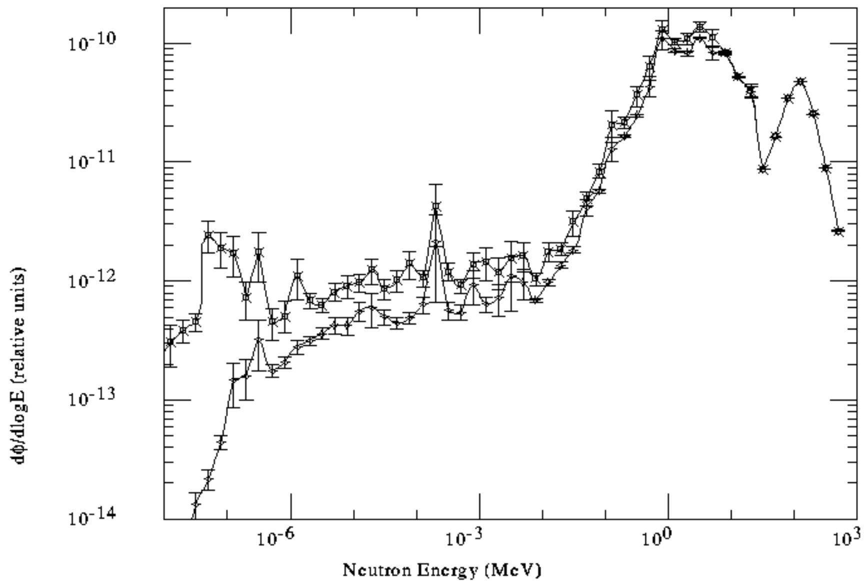


Figure 6

The influence of the presence of earth on the neutron energy-spectrum at the Olympus Gate EMS. 6.2 GeV protons incident on a thick Cu target at the Bevatron produce the source term. Two spectra per unit source neutron are shown: the upper curve shows the spectrum with the soil cylinder in place; the lower curve shows the spectrum without the soil cylinder (*i.e.* in air).

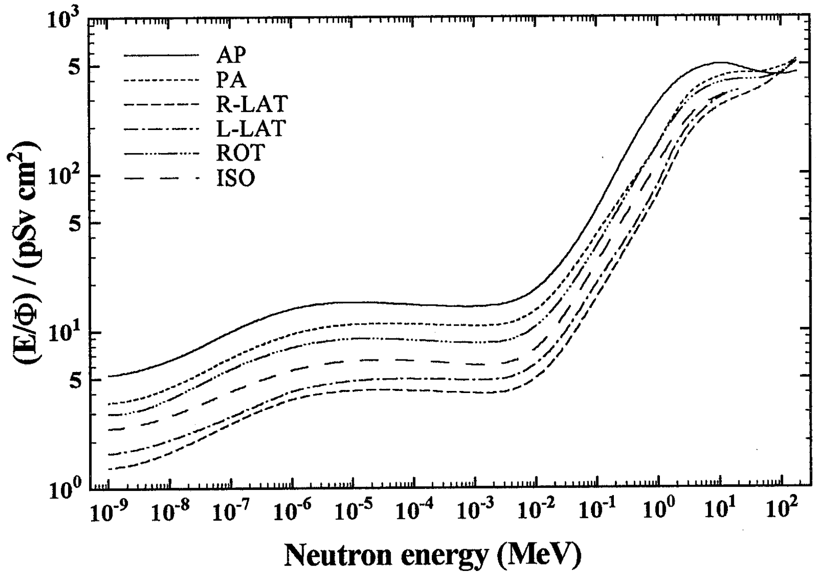


Figure 7.

Values of Neutron Fluence to Effective Dose Conversion Coefficients recommended by the ICRP and ICRU. Curves are shown for the standard ICRP/ICRU irradiation geometries over the energy range from thermal to 200 MeV (From ICRU Report 57)

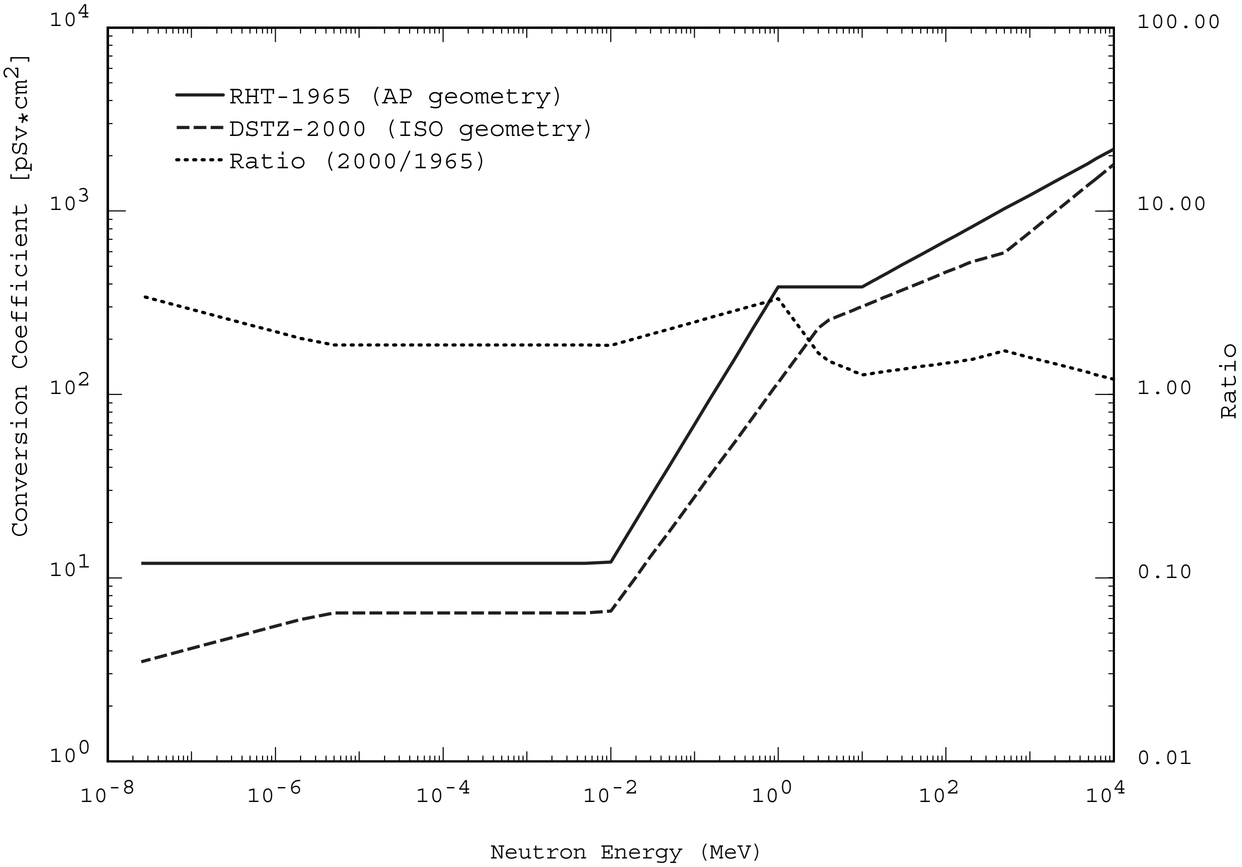


**Figure 8.**

A comparison of the fluence-to-dose-equivalent conversion coefficients RHT-1965 (AP) and DSTZ-2000 (ISO). The ratio of the values of the 2 sets of coefficients as a function of energy is also shown.

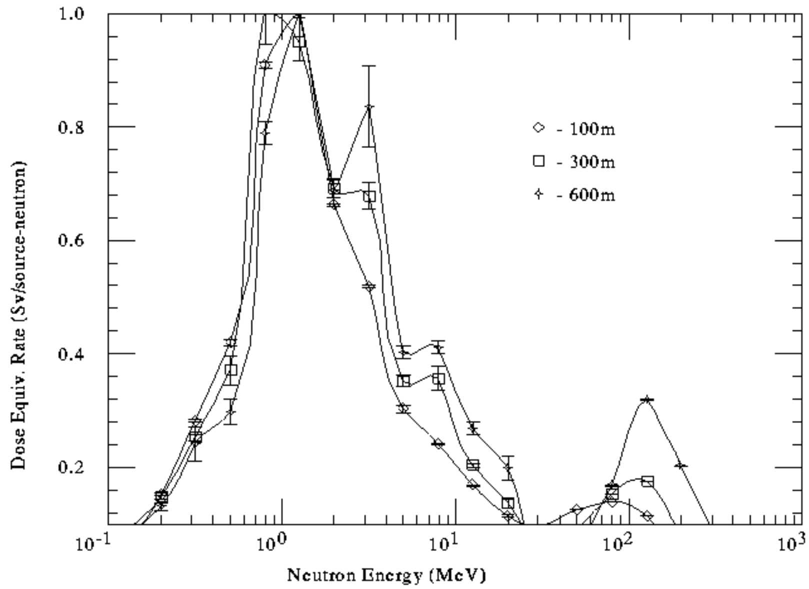


Figure 9

Dose Equivalent Spectra as a function of distance from the Bevatron. Three Curves are shown at 100 m, 300 m and 600 m from the Bevatron. The error bars indicate the statistical uncertainty of the calculated values